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Radiation conductance and directive gain of a ferrite based microstrip phased array antenna at X-band

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Abstract : A single frequency four element microstrip linear phased array antenna (MILIPAA), build-up on a typical ferrite substrate and resonating at frequency 10 GHz is presented. The effects of electroacoustic waves on the radiation properties of MILIPAA are investigated. It is noted that the radiation properties (radiation conductance and directive gain) are altered significantly with varying plasma contents. Despite it, ferrite based MILIPAA is more feasiable than the counterpart dielectric based array antenna.

Keywords : Phased array antenna, ferrite substrate, radiation properties

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1. Introduction

Microstrip antennas have received a great deal of attention in recent past [1–3], due to their many attractive features. Such antennas when mounted on board, space-borne vehicles encounter plasma medium during travel in space. It has been pointed out that the radiation properties of the microstrip antennas in plasma medium are modified to a great extent due to the generation of electroacoustic waves in addition to electromagnetic waves [4–6]. For better directional properties, array antennas are frequently used. The purpose of the present communication is to explore the possibility of realising more efficient and broad-band microstrip array antenna by building them on ferrite substrate. The substantial technological value of microwave ferrites mainly stems from the fact that they possess the combined properties of a magnetic material and an electric insulator [7–9]. In an earlier paper [10], we have discussed an analytical study of four element microstrip linear array antenna on a dielectric substrate. It is found that the free space value of directive gain was not sufficient for some specific purpose like radar, satellite *etc*. In the present paper, the above work has been extended to a ferrite based array antenna to get better radiation performance.

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2. Theoretical analysis

The expressions for radiated power in electromagnetic and plasma modes are derived using well-established hydrodynamic theory and vector wave function technique [11,12]. Using these expressions, the radiation conductance G_e and directive gain D_e of the MILIPAA are obtained for different values of plasma frequency. By substituting plasma frequency to zero, the free space results are achieved. Thus G_e and G_p may be defined as

$$G_e = 2P_e \tag{1}$$

$$G_p = \frac{2P_p}{..^2} \tag{2}$$

where P_e and P_p are the EM-mode and P-mode radiated power respectively.

The directive gain of the MILIPAA in a given direction is defined as the ratio of the radiation intensity in that direction to the average radiated power of the antenna It can be expressed as

$$D_e = \frac{4\pi U}{P_e}, \text{ for } \theta = \frac{3\pi}{4}, \phi = 0. \tag{3}$$

The geometry of the MILIPAA, which consists of four identical circular patches on a ferrite substrate of thickness h is shown in Figure 1.

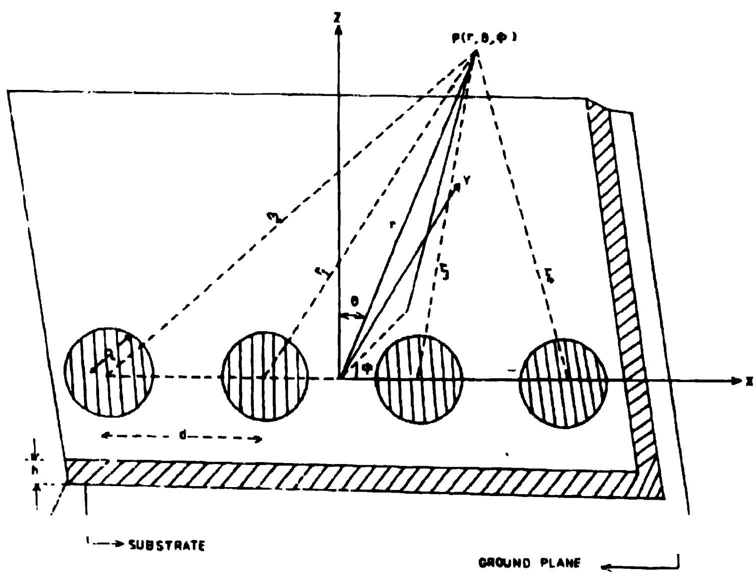

Figure 1. Configuration and coordinate system of the four element MILIPAA.

In this figure, all elements are equidistant (distance d) and are positioned along X-direction. These are fed by a coaxial line exciting TM mode. The location of the feed point is chosen so as to excite the desired mode and match the input impedance of the feed line [13,14].

The values of radius vector r_1, r_2, r_3 and r_4 (in the far zone field region) are calculated by applying the following approximations.

$$r_1 \approx r + 0.5\, d \cos\theta$$

$$r_2 \approx r + 1.5\, d \cos\theta$$

$$r_3 \approx r - 0.5\, d \cos\theta$$

$r_4 \approx r - 1.5\, d \cos\theta$, for phase variation and $r_1 \approx r_2 \approx r_3 \approx r_4 \approx r$, for amplitude variation.

Following our earlier work [10] and above criteria, using theory of ferrite materials and neglecting coupling between the patches [15], the radiated power in EM mode (P_e) and plasma mode (P_p) are determined by integrating the Poynting vector over a large sphere. Thus, the expressions for P_e and P_p are obtained as follows :

$$P_e = \frac{(\beta_e a)^2 V_0^2}{960\pi} \int_0^{2\pi}\int_0^{\pi}\left[\left\{J_n'(\beta_e a \sin\theta)\cos n\phi\right\}^2 + \right.$$

$$\left.\left\{\frac{J_n(\beta_e a \sin\theta)}{\beta_e a \sin\theta} \sin n\phi \cos\theta\right\}^2\right] \times \cos^2\left\{0.5(\beta_e d \cos\theta + \beta_1)\right\}$$

$$\times \cos^2(\beta_e d \cos\theta + \beta_1)\sin\theta\, d\theta\, d\phi \tag{4}$$

and

$$P_p = \frac{15\pi(1-A^2)V_0^2}{A}\left(\frac{C}{v}\right)\int_0^{2\pi}\int_0^{\pi}\left[\frac{\sin(\beta_p h \cos\theta)}{\beta_p h \cos\theta} J_n(\beta_p a \sin\theta).\sin n\phi\right]^2$$

$$\times \cos^2\{0.5(\beta_p d \cos\theta + \beta_1)\}\cos^2(\beta_p d \cos\theta + \beta_1).\sin\theta\, d\theta\, d\phi \tag{5}$$

where a is the radius of each patch and v is r.m.s. thermal velocity of the electron. β_e and β_p are the propagation constants for EM mode and plasma mode respectively, given by

$$\beta_e = \frac{2\pi}{\lambda_0}\sqrt{\mu_{eff}}\, A; \beta_p = \beta_e\left(\frac{c}{v}\right),$$

and

$$A = \left(1 - \frac{\omega_p^2}{\omega_0^2}\right)^{1/2}.$$

Here, ω_p and ω_0 are plasma and source frequencies respectively ; β_1 is the phase excitation between the excitation voltages of the elements and V_0 is the peak voltage at $\phi = 0$.

Using (3), the directive gain of the MILIPAA, D_e can be obtained in the following manner :

$$D_e = \frac{4\pi M_e}{\int_0^{2\pi}\int_0^{\pi} M_e \sin\theta d\phi}, \text{ for } \theta = \frac{3\pi}{4}, \phi = 0, \tag{6}$$

where

$$M_e = \left[\left\{J_n'(\beta_e a \sin\theta)\cos n\phi\right\}^2 + \left\{\frac{J_n(\beta_e a \sin\theta)}{\beta_e a \sin\theta}\sin n\phi \cos\theta\right\}^2\right.$$

$$\times \cos^2\left\{0.5(\beta_e d\cos\theta + \beta_1\right\}\cos^2(\beta_e d\cos\theta + \beta_1). \tag{7}$$

In expressions (4), (5) and (7), the array factor $\cos\{0.5(\beta_e d\cos\theta + \beta_1\}$ $\cos(\beta_e d\cos\theta + \beta_1)$ has been taken in normalized form. Since power received by the receiving antenna is in the form of e.m.wave only, so power radiated as a plasma (electroacoustic) wave is going wasted and need not be calculated.

3. Results and discussion

We have estimated two important radiation properties *viz*. radiation conductance G_e and directive gain D_e for the four element MILIPAA which is built on a typical ferrite substrate $Ni_{1.062}Co_{0.02}Fe_{1.984}O_4$ (μ_{eff} = 14.78 and ε_r = 14.78) with varying ratios of plasma to source frequency (ω_p/ω_o). For a direct and meaningful comparison with dielectric based array antenna [10], we have used the same input values *viz*. f_r = 10 GHz, a = 0.47 cm, $d = 0.5\,\lambda_0$ and phase excitation $\beta_1 = \pi/2$ for both the antennas. The calculated values of G_e and D_e are presented in Table 1.

Table 1. Calculated values of radiation conductance G_e and directive gain D_e for four element MILIPAA with different plasma contexts.

S No	$\frac{\omega_p}{\omega_o}$	Plasma parameter A	Radiation conductance G_e ($\times 10^{-4}$ mho)		Directive gain D_e (dB)	
			Ferrite based MILIPAA	Dielectric based (Ref. [10])	Ferrite based MILIPAA	Dielectric based (Ref [10])
1.	0	1.0	8.1325	2.0048	8.4939	5.9225
2	0.1	0.995	10.6831	2.0037	7.4545	5.9737
3	0.2	0.980	11.6230	2.0996	7.5150	6.0250
4	0.3	0.954	12.0209	2.1332	7.4783	6.1340
5.	0.4	0.917	10.3869	2.2095	7.0989	6.2225
6.	0.5	0.866	6.1202	2.2301	5.8565	6.3993
7.	0.6	0.8	1.3987	2.1540	2.0243	6.4737
8.	0.7	0.714	0.1379	1.8549	1.1504	6.5980
9.	0.8	0.6	3.6294	1.2914	0.0233	6.5974
10.	0.9	0.436	1.4992	0.5102	0.0093	6.3803
11.	0.99	0.141	0.9935	0.0079	-	4.9677
12.	1.1	0	0	0	0	0

It is found from Table I that the free space values of G_e and D_e for the ferrite based MILIPAA are significantly higher than those reported for dielectric based array antenna. However, both cases exhibit zero response when the value of plasma frequency (ω_p) approaches source frequency (ω_0). To observe a sharp contrast, we have plotted these values in Figure 2 with respect to (ω_p/ω_0).

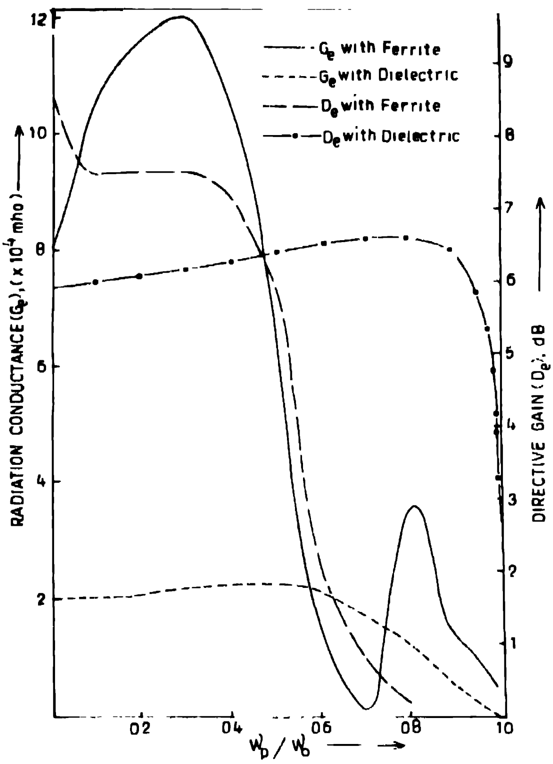

Figure 2. Variation of radiation conductance G_e and directive gain D_e with plasma to source frequency for four element MILIPAA

It is noticed from Figure 2 that the value of G_e for ferrite based MILIPAA first increases, reaches to a peak value and then decreases. Again it increases and finally decreases and becomes zero at $\omega_p \approx \omega_0$. The first and second peaks are observed around at $\omega_p / \omega_0 = 0.3$ and $\omega_p / \omega_0 = 0.8$ respectively. A similar peak was also observed earlier [6,10]. In between two peaks, the MILIPAA shows a faster drop in G_e as compared to dielectric based array. Thus, above a certain value of ω_p / ω_0, the value of integral determining the value of G_e [*eq.* (4)] starts to decrease rapidly.

A comparative study of the directive gain D_e for these two arrays is also made in Figure 2. Upto $\omega_p / \omega_0 = 0.5$, the directive gain of ferrite based MILIPAA is higher than the corresponding values of dielectric based antenna. Beyond it, the variations of D_e with ω_p / ω_0 are found to differ appreciably from each other for the two arrays. For the present study, it starts to decrease rapidly, as a matter of fact it becomes almost zero before reaching $\omega_p = \omega_0$. On the other hand, D_e for dielectric based array antenna first increases and attains a peak value at $\omega_p \equiv 0.8\omega_o$. Finally, it decreases very fast and becomes zero at $\omega_p = \omega_o$. The peaks found in the plots of D_e and G_e seem to be related to the geometrical factors of the arrays. It is pertinent to mention that the peak in G_e for MILIPAA is more prominent than the peak in D_e for dielectric based array antenna.

To conclude, despite having some discontinuities for higher frequency plasma regions, the present study is supposed to be useful for several practical applications, particularly for space – borne vehicles because such type of array antennas can be mounted on the flat surfaces of such vehicles. Recently, the implementation of the microstrip array has also been seen into the radar and other communication systems.

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